1 Experiments

1.1 STAR

1.1.1 Recent spin-related upgrades

A cross-sectional view of the STAR detector, emphasizing the subsystems that have been added to the baseline detector [**?**] with the spin program as a primary driver, is shown in Fig. **??**. The relative luminosity monitoring critical for the measurement of spin asymmetries is provided by Beam-Beam Counters (BBC) that have been added just to the east and west of the STAR magnet, at a distance of 3.5 m from the beam intersection point. The BBC's are plastic scintillating tile detectors for charged particles over the pseudorapidity range $3.3 < \eta < 5.0$. An east-west prompt coincidence, sensitive to nearly 90% of the total non-singly diffractive pp cross section at $\sqrt{s} = 200$ GeV, is used to discriminate beam collisions from beam-gas interaction background. The azimuthal segmentation of the scintillating tiles permits the measurement of left-right and up-down single-spin asymmetries. Comparison of the BBC asymmetries measured at STAR for hits in the inner BBC tiles with those measured simultaneously in the RHIC CNI polarimeters has revealed a small analyzing power ($A_N \approx 0.006$) suitable for use of the BBC's as a local polarimeter when the beam spin at STAR is transverse to its momentum. In particular, this functionality is important for tuning the STAR spin rotators: as shown in Fig. 2, one can adjust the rotator magnet currents to give longitudinal polarization at the IR by arranging for both (left-right and up-down) BBC transverse asymmetries to vanish.

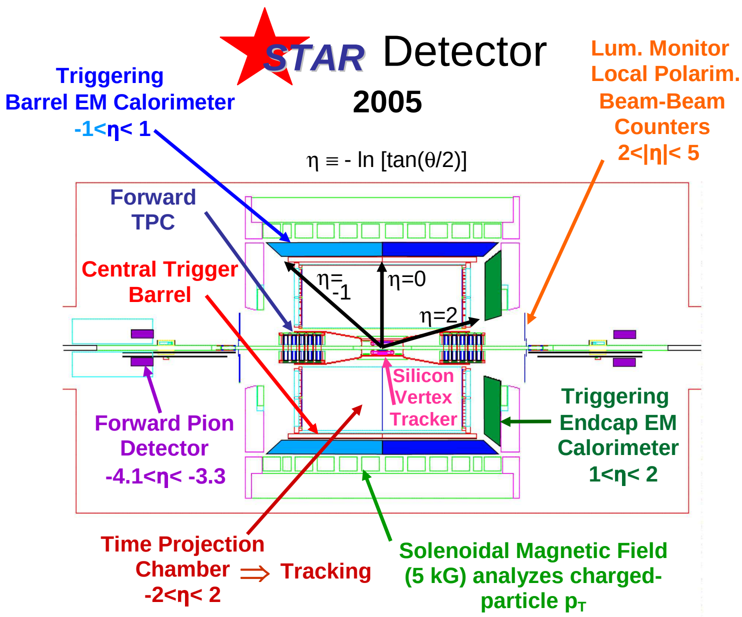

Figure 1: *Cross sectional view of the STAR detector as installed for the 2005 RHIC run, emphasizing subsystems most relevant for the spin program, and their functions. Completion of the readout electronics for the barrel EMC during the 2005 run will make the detection subsystems used for p+p fore-aft symmetric, except for the endcap EMC, which resides on the west side.*

The major STAR upgrades already installed for the spin program represent additions of electromagnetic calorimetry (EMC) for the detection of high-energy photons, electrons and π^0 over a broad range of pseudorapidity. The Forward Pion Detectors (FPD) are small lead-glass-based calorimeters placed to the left and right, and above and below, the beam lines 7.5 m to the east and west of the center of STAR. The FPD provides π^0 detection and identification at high $x_{Feynman}$ and forward rapidity ($3.3 < \eta < 4.1$), where large single-spin transverse asymmetries have been observed (see Fig. **??**). (The measurements reported in [**?**] were made with a precursor of the present FPD's that was a prototype section of the STAR Endcap EMC.) The FPD's will continue to be used to probe the origins of these large single-spin effects, and also to investigate gluon polarization via di-hadron coincidence measurements of the type discussed in Sec. **??**. In addition, the FPD provides access in d+Au collisions at STAR to the low Bjorken-x regime where gluon saturation models predict, and the RHIC experiments have observed, the onset of significant suppression of moderate-p_T hadron production. A new calorimeter described below is planned to greatly expand the coverage of STAR's west-side FPD to enhance the above coincidence measurements in both p+p and d+Au runs.

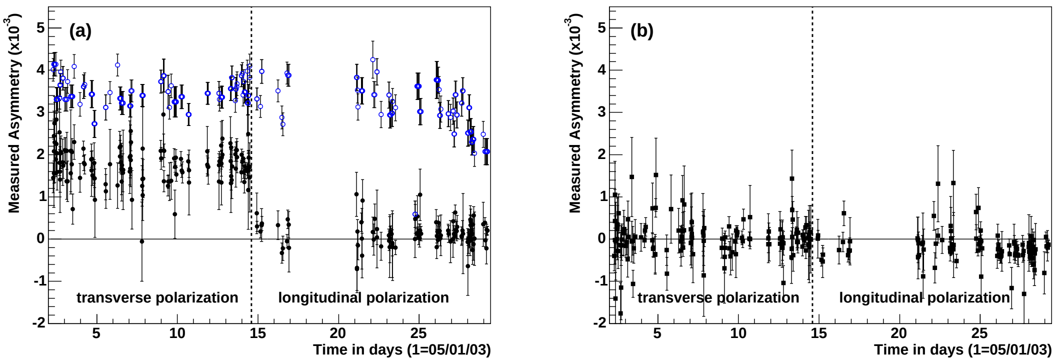

Figure 2: *Left-right (a) and up-down (b) single-spin asymmetries measured vs. time during the 2003 p+p run with the STAR BBC's (closed symbols) and the RHIC CNI polarimeters (open symbols). When the beam spin orientation at STAR was vertical, the left-right asymmetry was consistently about half that of the CNI polarimeters. Initial tuning of the STAR spin rotators to produce longitudinal polarization was carried out on day 14, by arranging for both BBC transverse asymmetries to vanish, while the CNI asymmetries remained sizable.*

The largest additions to STAR relevant to the spin program are the Barrel (BEMC [**?**]) and Endcap (EEMC [**?**]) calorimeters, funded by DOE and NSF, respectively. Each of these subsystems is a multi-layer sandwich of Pb radiator sheets and plastic scintillator with light collection via optical fibers. Each contains a fine-grained Shower-Maximum Detector (SMD – gaseous for BEMC, plastic scintillator for EEMC) for discriminating single photons from π^0 daughter photon pairs, by means of the transverse shape of the electromagnetic showers produced. Each also contains pre-shower layers, and the endcap adds a post-shower layer as well, to improve electron/hadron discrimination. As shown in Figs. 3, the fabrication and installation of both EMC's has been completed during 2004, although installation of final readout electronics for the east half of the BEMC is still anticipated to occur during February-March 2005. The EMC's provide critical detection and triggering capability for STAR studies of jets, photons, π^0, W-bosons and J/ψ (as well as heavier quarkonium species), all of which play significant roles in the spin program described in earlier sections of this document. The broad pseudorapidity coverage ($-1 \leq \eta \leq 2$)

permits, for example, study of γ-jet coincidences spanning a broad range of x-values for the participating gluons, while still maintaining large transverse momenta ($p_T > 5$ GeV/c) for the partonic scattering.

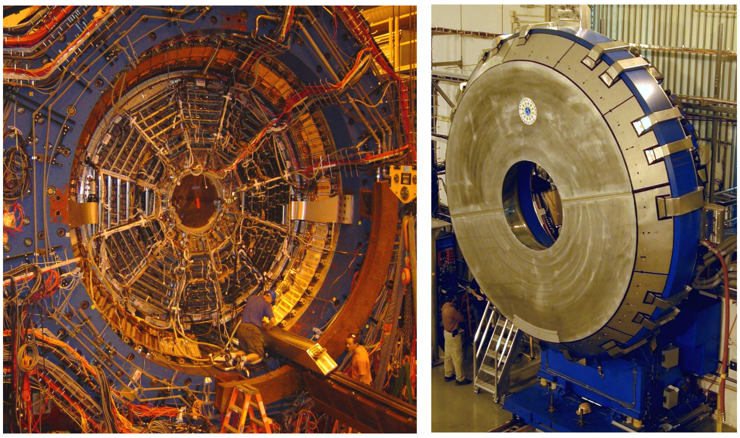

Figure 3: *Photographs showing insertion of one of the final barrel EMC modules into STAR (left) and the complete endcap EMC on the west poletip (right). With completion of these subsystems, STAR is ready to take full advantage of long polarized p+p runs in the 2005-9 period.*

Both EMC's have performed well in partial installations for the 2003 and 2004 RHIC runs, enabling detector commissioning, optimization of online calibration and triggering, debugging of subtle electronics problems and initial extraction of physics results. The first paper based on BEMC transverse energy measurements for Au+Au collisions at STAR has already been published [**?**]; others, based on electron spectra measured with the BEMC, are in preparation. Figure 4 shows an event display for a dijet detected with STAR's TPC and BEMC, together with the spectrum of the ratio of BEMC/total transverse energy for jets reconstructed within the partial BEMC acceptance available during the 2004 p+p RHIC run. Figure 5 shows a typical shower profile measured with the EEMC Shower-Maximum Detector for a pi^0 candidate, together with an invariant mass spectrum reconstructed from the SMD and calorimeter tower information for all two-cluster combinations detected with the partial EEMC for several 2004 p+p runs. Analysis groups within STAR are actively working on optimizing the efficiency and background suppression in reconstruction algorithms for jets, π^0 and single photons, electrons and J/ψ. This work is aiming toward first EMC-based spin publications in the latter half of 2005 (based on 2003 and 2004 data) and toward readiness for prompt analysis of results from the anticipated long p+p run during 2005.

In addition to the above hardware upgrades, STAR has enhanced its spin program by the addition of new collaborators over the past few years. Prominent new groups with heavy interest in spin from MIT, LBNL, CalTech and Valparaiso University complement the groups from BNL, ANL, Indiana University, UCLA, Penn State, Texas A&M University, JINR Dubna and IHEP Protvino, who have been instrumental in launching STAR's spin program. With these hardware and manpower additions, the resources are in place to permit STAR to address many of the high priority spin physics goals described in Sec. 2, most prominently the delineation of gluon helicity preferences via a number of reaction channels. Learning curves, but no additional equipment, are anticipated for dealing most effectively with the TPC pileup and BBC occupancy problems that will arise as the p+p luminosity increases at RHIC, and for monitoring beam polarization locally

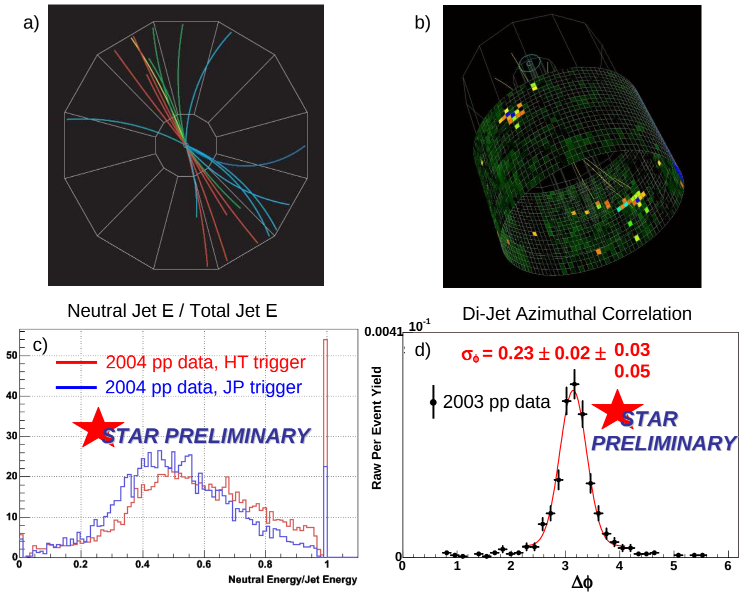

Figure 4: *Event displays showing tracks reconstructed from a p+p di-jet event in the STAR TPC (a) and from the TPC and BEMC (b). The events were collected during the 2004 run, when only the west half of the BEMC was functional. The lower frames show preliminary STAR p+p jet physics results: (c) the spectrum of the ratio of BEMC to total (TPC+BEMC) energy measured for inclusive jets, for two different jet triggers; (d) the distribution of azimuthal angle differences between the reconstructed jet axes for di-jet events [**?**]. The differences between the two spectra in (c) reflect trigger biases (qualitatively consistent with simulations) that must be understood to extract reliable information concerning gluon polarization from measured jet two-spin asymmetries. The fit to the angular correlation in (d) is used to extract the mean transverse momentum $\langle k_T \rangle$ of the interacting partons before the hard scattering that produces the di-jet. STAR's results for $\langle k_T \rangle$ are consistent with the world data for p+p at other collision energies [**?**].*

at STAR when the beam spins are oriented longitudinally. However, additional upgrades are needed, as described below, to optimize W detection and the measurement of flavor-dependent sea antiquark polarizations in STAR.

1.1.2 Future STAR upgrades relevant to the spin physics program

The $W^{\pm}$ production studies central to the envisioned spin physics program at $\sqrt{s} = 500$ GeV strain the capabilities of STAR's Time Projection Chamber, which was designed for heavy-ion collisions to track charged particle momenta up to $p_T \sim 10$ GeV/c. The TPC provides very limited resolution for W daughter leptons up to p_T of 40 GeV/c, especially in the endcap region ($\eta > 1$), where the drifting electrons from charged particle tracks intercept a decreasing fraction of the readout pad rows. Fortunately, the EMC's provide measurements of electron transverse energy with a typical resolution $\sim 4\%$ for $p_T \approx 40$ GeV/c. But the EMC's alone cannot discriminate electrons from positrons, and charge sign determination for the parent W is critical to the physics goal of separating $\overline{u}$ from $\overline{d}$ polarizations in the proton sea (see Sec. **??**). Furthermore, comparison of p_T measured from track curvature with E_T measured in the calorimeters provides

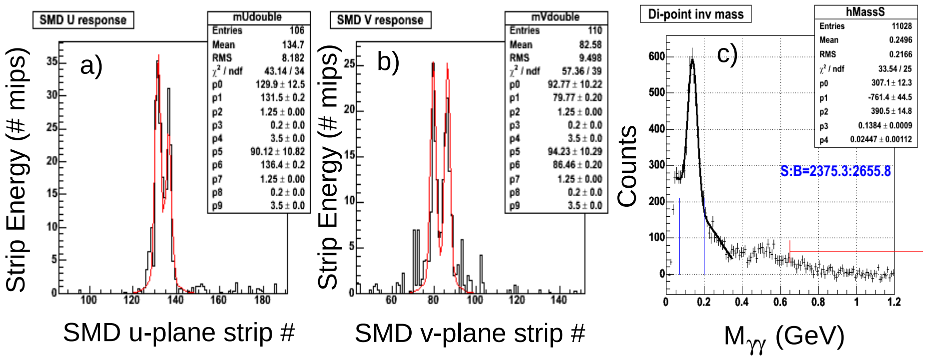

Figure 5: *Elements of π^0 reconstruction with the STAR EEMC. Frames (a) and (b) show transverse electromagnetic shower profiles measured in two orthogonal SMD planes for a single event with a 14 GeV π^0 candidate detected during the 2004 RHIC p+p run (when one third of the SMD was functional). Frame (c) shows the invariant mass spectrum reconstructed for several p+p runs from all possible pairings of EEMC points in the calorimeter towers and SMD strips. The π^0 peak is prominent. Algorithm development to optimize reconstruction efficiency and resolution, and discrimination of single photons from π^0 is ongoing.*

a powerful method (over and above those available from the EMC's alone) to discriminate the weak W signal from a background of more abundant high-p_T charged hadrons. While STAR's present tracking capabilities are adequate for these tasks in the BEMC region, upgraded tracking is needed for $W^\pm$ production in the endcap region, where the separation of $\overline{u}$ from $\overline{d}$ polarizations is kinematically cleanest (see Sec. **??**).

The need for improved endcap tracking is demonstrated in Fig. 6 by simulations of 30 GeV/c pion tracks, whose sagitta in the middle of the endcap region is $\approx$ 2.5 mm. With the TPC alone, the charge sign is misidentified about 15-20% of the time. The addition of three space points measured with $\sim 50\mu$m resolution near the vertex and two with $\sim 100\mu$m resolution just in front of the endcap would completely remove the charge misidentification problem, and would provide 30% relative p_T resolution at the high momenta of relevance to the W production program. Improvements of this order are quite feasible with the arrangement of detectors outlined below, and would greatly enhance the physics impact of STAR's W measurements.

The conceptual designs presently under consideration for upgraded forward tracking in STAR are illustrated in Fig. 7. Space points near the vertex would be provided by an array of annular silicon strip detectors placed just downstream of STAR's vertex tracking devices, and inside the TPC's inner field cage. Position would be measured just upstream of the EEMC in an array of 3-layer Gas Electron Multiplier (GEM) chambers [**?**] tiling the pseudorapidity region $1 < \eta \leq 2$, over the full azimuthal acceptance. The silicon disks would be integrated with and extend the coverage of a new barrel silicon-strip tracker envisioned to surround, and provide high-rate tracks pointing to, a high-resolution Advanced Pixel Sensor micro-vertex detector (the Heavy Flavor Tracker, HFT). The primary motivation for the latter two subsystems comes from the needs for high-quality measurements of slightly displaced vertices associated with heavy quark production in STAR heavy-ion collisions. Research and development on the type and size of GEM chambers that would be needed for the endcap tracker is ongoing in a collaboration between STAR and PHENIX. In addition to the ability to obtain the needed spatial resolution with thin chambers that

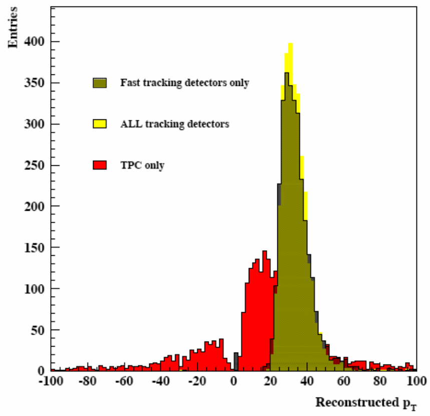

Figure 6: *Tracking simulations for the endcap pseudorapidity region ($1 < \eta < 2$) in STAR, showing the p_T response to 30 GeV/c thrown π^- under various assumptions of tracking detectors. With the TPC alone, at present performance levels, the p_T resolution is poor, and the charge sign is mistaken $\sim 20\%$ of the time. With a forward tracking upgrade the resolution will be sufficient for the $W^\pm$ production program, and the charge sign errors will be removed. The simulation here assumes measurement of three space points with 50 μm resolution inside the TPC inner field cage and of two space points with 100 μm resolution just in front of the EEMC.*

would fit within the narrow space available in front of the EEMC, the GEM technology provides fast detectors whose tracking information would significantly alleviate ambiguities from pileup tracks in the TPC anticipated at the ultimate RHIC pp luminosities.

STAR groups from MIT and Lawrence Berkeley National Laboratory are leading a collaboration of several institutions (including ANL, BNL, IUCF, Yale and Zagreb) in planning the inner and endcap tracking upgrades. (The heavy-ion-driven HFT upgrade project is led by the LBNL group.) The conceptual design of the silicon disks and GEM chambers is not yet complete, with still important open issues to address concerning the optimal tradeoffs between coverage and cost, the resolution impact of material in the endcap of the TPC, etc. The present plan is to proceed with this upgrade in two stages: first, the silicon barrel would be proposed, with the goal of fabricating and installing it in STAR in time for an FY09 RHIC run, when it would be needed to get optimal usage from the HFT (which is to be proposed on a slightly faster timeline); the silicon disks and GEM chambers would be proposed about a year later, with the goal of installation for a long 500 GeV pp run in FY10, when we would hope to collect a large fraction of the statistics needed for the W production A_L measurements. The rough funding scope anticipated for these two phases is $\sim$ \$6M and \$5M, respectively, with contingency. Both DOE and NSF funding are likely to be sought to share the costs for the second phase.

Additional planned STAR upgrades driven by the heavy-ion research program will also have significant benefits for the p+p spin measurements. An extension of STAR's forward electromagnetic calorimetry coverage beyond the EEMC, to 2.5 $\lesssim \eta \lesssim$4, has been proposed to the NSF in January 2005. This Forward Meson Spectrometer (FMS) (see Fig. 8) would be constructed from existing lead-glass counters to replace and expand the present Forward Pion Detector on STAR's west side. The primary motivation for the FMS is to probe the contributions of gluons to nuclear structure at very low Bjorken x (down to $x \sim 0.001$) in proton-nucleus or deuteron-nucleus collisions at RHIC. Gluon saturation models predict a suppression of hadron production at moderate

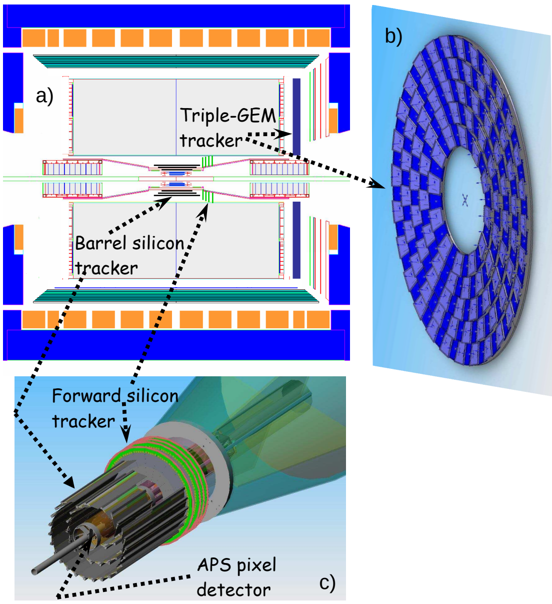

Figure 7: *Schematic illustration of one layout of silicon and GEM detectors presently under consideration for STAR's tracking upgrades. In (a) the various components of the staged tracking upgrade are shown in their intended locations within the STAR detector. Frame (b) shows the layout of triple GEM chambers envisioned to tile the region in front of the EEMC. Frame (c) shows the inner tracking region, including four silicon disks considered as part of the forward tracking improvement driven by the spin program. The other proposed subsystems highlighted in (c) – a fast barrel silicon tracker (supplanting STAR's current Silicon Vertex Tracker) and an Advanced Pixel Sensor micro-vertex detector – address needs for heavy flavor tracking in the heavy-ion program. The forward silicon tracker must be integrated with them and the associated changes they require in the beam pipe through the central region of STAR.*

p_T in this forward rapidity region, which can be tested by systematic measurements for mesons reconstructed from their daughter photons. Furthermore, Color Glass Condensate approaches to high-density QCD treat the gluons at such low x and at moderate momentum transfers as a classical field, from which parton scattering will result in mono-jet, rather than traditional di-jet, products. The FMS will allow searches for the onset of such mono-jet events as a function of the rapidity interval between correlated pairs of hadrons (*e.g.*, π^0) detected in coincidence within STAR's extended EMC coverage.

Similar coincidences between leading hadrons in polarized p+p collisions permit study of parton-parton scattering spin sensitivities under conditions where one can vary the subprocess (qq vs. qg vs. gg) contributions in a controlled manner. As described in Sec. 2.4.1 of this document, $A_L L$ measurements for such di-hadron events are part of the planned approach toward unraveling the polarization of gluons in a polarized proton. Furthermore, A_N measurements for mesons in the FMS, in coincidence with other jet fragments, will probe the origin of the large single-spin asymmetries already found (see Fig. **??**) for forward π^0 production, as described in Sec. 2.5. Thus, the spin program would make substantial use of the FMS once it is installed in STAR.

It is hoped the FMS will be installed for the FY07 RHIC run, when STAR's present plans call

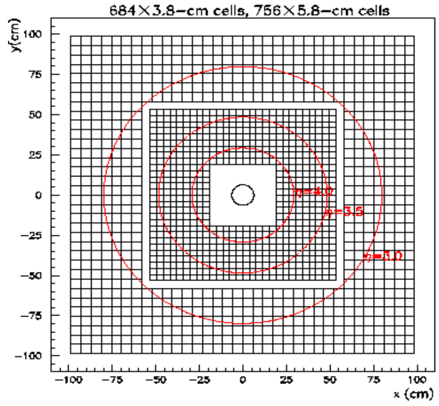

Figure 8: *Front view of the intended layout of Pb-glass counters comprising the proposed Forward Meson Spectrometer (FMS) at STAR. The detector would replace the current west Forward Pion Detector located 7.5 m from the center of STAR, greatly expanding acceptance for mesons decaying to photons and for meson coincidences in a kinematic region dominated by contributions from gluons at very low Bjorken x. This coverage is important to both the search for saturation of gluon densities in nuclei and to the STAR spin program. The pseudorapidity coverage is indicated by the red circles representing loci at η = 3.0, 3.5 and 4.0.*

for the next long d+Au collision run. Total funding needed for this project is about $1M, with most of this to be supplied by NSF. The project is being led by STAR physicists from Penn State University, BNL and IHEP Protvino, with additional participation by LBNL and Texas A&M University. The lead-glass cells would be taken from the existing STAR west-side FPD and from an available supply owned by the Protvino group.

The case for other STAR upgrades driven by the heavy-ion program is summarized in the STAR Decadal Plan [**?**]. An upgrade to the TPC front-end readout electronics and to the STAR Data Acquisition system will increase the event rate capability from the present ~ 100 Hz to ~ 1000 Hz, by 2007-8. This upgrade has two significant implications for the spin program: the FEE upgrade will free up space directly in front of the EEMC, needed for eventual installation of the endcap GEM tracker described above; the DAQ upgrade will permit collection of large data samples for abundant reaction channels, such as inclusive jet or π^0 production at moderate p_T, without introducing sizable and undesirable dead time for the rarer channels, such as direct photon production. The barrel Time-Of-Flight detector proposed to improve (by 2008) STAR's particle identification up to ~ 3 GeV/c in heavy-ion collisions will also aid the spin program, *e.g.,* in permitting clean identification of charged pions, and hence of the ρ-meson invariant mass region, for studies of transversity via interference fragmentation functions (see Sec. 2.5). The Heavy Flavor Tracker mentioned above, while again driven by studies of the unique matter produced in heavy-ion collisions, will also permit improved identification in STAR of the production of heavy quarks in p+p collisions, providing access to gluon polarization and to possible spin effects from the quark mass (explicit chiral-symmetry-breaking) terms in the QCD Lagrangian.

In summary, the completion of the barrel and endcap EMC's, following the addition of the Beam-Beam Counters and Forward Pion Detectors, has brought STAR to full readiness to exploit the anticipated long polarized pp collision runs during the 2005-9 period. A significant upgrade to STAR's forward tracking capabilities is still needed to optimize its $W^{\pm}$ production program in 500 GeV pp runs anticipated for the 2009-12 period. Other STAR upgrades planned for the next several years, primarily to enhance its capabilities in studying heavy-ion collisions, will have significant side benefits for the spin program.